

Merging Rates of the First Objects and the Formation of First Mini-Filaments in Models with Massive Neutrinos

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ABSTRACT

We study the effect of massive neutrinos on the formation and evolution of the first filaments containing the first star-forming halos of mass $M \sim 10^6 M_\odot$ at $z \sim 20$. With the help of the extended Press-Schechter formalism, we evaluate analytically the rates of merging of the first star-forming halos into zero-dimensional larger halos and one-dimensional first filaments. It is shown that as the neutrino mass fraction f_ν increases, the halo-to-filament merging rate increases while the halo-to-halo merging rate decreases sharply. For $f_\nu \leq 0.04$, the halo-to-filament merging rate is negligibly low at all filament mass scales, while for $f_\nu \geq 0.07$ the halo-to-filament merging rate exceeds 0.1 at the characteristic filament mass scale of $\sim 10^9 M_\odot$. The distribution of the redshifts at which the first filaments ultimately collapse along their longest axes is derived and found to have a sharp maximum at $z \sim 8$. We also investigate the formation and evolution of the second generation filaments which contain the first galaxies of mass $10^9 M_\odot$ at $z = 8$ as the parent of the first generation filaments. A similar trend is found: For $f_\nu \geq 0.07$ the rate of clustering of the first galaxies into the second-generation filaments exceeds 0.3 at the characteristic mass scale of $\sim 10^{11} M_\odot$. The longest-axis collapse of these second-generation filaments are found to occur at $z \sim 3$. The implications of our results on the formation of massive high- z galaxies and the early metal enrichment of the intergalactic media by supernova-driven outflows, and possibility of constraining the neutrino mass from the mass distribution of the high- z central blackholes are discussed.

Subject headings: cosmology:theory — large scale structure of Universe

1. INTRODUCTION

In 1970, Zel’dovich suggested that the large-scale structure of the Universe such as sheets and filaments form through the anisotropic collapse of large-scale density fluctuations along the principal axes of the gravitational tidal fields (Zel’Dovich 1970). Although his original model assumed a hot dark matter cosmology, this picture can be well accommodated even by the currently popular Λ -dominated cold dark matter (Λ CDM) cosmology (Bond et al. 1996). The dark matter halos that condense out first on the smallest scales merge anisotropically along the principal axes of the tidal fields into larger and larger structures. The inherent anisotropic nature of the gravitational merging process leads to the formation of filament-like and sheet-like structures, as envisioned by Zel’dovich’s model. The nonlinear evolution of the tidal shear fields sharpens the anisotropic interconnection of the large-scale structure (which is often called the cosmic web), developing a hierarchical system where small filaments are threaded with the larger parent filaments (e.g, Springel et al. 2005). To understand the formation and evolution of the large-scale structure, an important question to answer is how frequently the halos merge into filaments and under what circumstances the halo-to-filament merging event occurs efficiently.

Lacey & Cole (1993, 1994) have for the first time evaluated analytically the merging rates of bound halos by extending the original Press-Schechter formalism (Press & Schechter 1974). Their analytic work was later refined and complimented by numerical calculation of merger trees from N-body simulations (Somerville et al. 2000). Recently, Fakhouri & Ma (2008) constructed merger trees from the large Millennium Run halo catalogs (Springel et al. 2005) and found that the mean merging rate per halo can be well modeled by a nearly universal fitting formula. In addition, Fakhouri & Ma (2008) showed that the prediction of the extended Press-Schechter formalism for the halo merging rates disagrees with the numerical results from the Millennium Run halo catalog by up to a factor of a few.

The halo-to halo merging rates were originally derived under the assumption that the merging events occur in a hierarchical way. If the matter content of the Universe were composed purely of CDM particles, then the structure formation would proceed in a strictly hierarchical way. However, if the non-CDM particles (either warm or hot) coexist with the CDM particles, the pure hierarchy in the build-up of the large-scale structure would break down at some level, depending on their mass fraction (Yoshida et al. 2003). True as it is that the current observations put a tight constraint on the amount of the possible non-CDM particles, they have not been completely excluded. As a matter of fact, the existence of non-CDM particles have been suggested as one possible solution to alleviate the apparent mismatches between observations and the predictions of Λ CDM cosmology on the subgalactic scales (see Boyanovsky et al. 2008; Kuzio de Naray et al. 2010; de Vega & Sanchez 2010, for

a recent discussion).

Among the various candidates for the non-CDM particles, the massive neutrinos have so far attained the most serious attentions. Ever since it was discovered that at least one flavor of the neutrinos must be massive and that the neutrino masses would be best constrained from the astronomical data (see Lesgourgues & Pastor 2006, for a review), a flurry of research has been conducted to quantify the effect of massive neutrinos on the formation and evolution of the large-scale structure (e.g., Bond et al. 1980; Doroshkevich et al. 1981; Hu 1998; Hu & Eisenstein 1998; Valdarnini et al. 1998; Eisenstein & Hu 1999; Lewis & Challinor 2002; Seljak et al. 2006; Tegmark et al. 2006; Saito et al. 2009; Shoji & Komatsu 2010). In previous studies of the structure formation in a Λ MDM (Λ +CDM+massive neutrinos) universe, what has been largely focused is the suppression of the small-scale powers in the density power spectrum due to massive neutrino’s free-streaming and its effect on the structure formation.

Since the massive neutrinos would decrease the merging rates of the small-scale halos due to their free streaming, one would naively think that the formation of large scale structures would be deferred in a Λ MDM universe. Meanwhile, the recent discovery of high- z quasars at $z \geq 6$ (Fan et al. 2001; Fan 2003; Fan et al. 2004, 2006; Jiang et al. 2009; Willott et al. 2009, 2010) has suggested that the first galaxies of mass $\geq 10^8 M_\odot$ must have formed at redshifts $z \geq 8$. At first glance the existence of such massive first galaxies at such early epochs might look difficult to reconcile with a Λ MDM model. Even in a Λ CDM cosmology, it is not so easy to explain the existence of the high- z quasars since it requires very high merging/accretion rate in the early Universe.

Yet, what has not been noted in previous works is that the presence of massive neutrinos may actually open a new channel for the rapid structure formation. Since the massive neutrinos would behave as effective warm dark matter (WDM) particles, they would fasten the collapse of matter along the major axes of the gravitational tidal fields on large scales. In other words, while the free-streaming of massive neutrinos slows down the formation of the zero-dimensional bound halos on small scales, it speeds up the formation of one-dimensional filaments on larger scales. The filaments are the most optimal environments for the rapid accretion of gas and matter. Furthermore, when the filaments collapse along their longest axes, they would provoke the violent merging of the constituent halos.

Here, assuming a Λ MDM universe, we study how the first filaments form through the clustering of the first star-forming halos and how they evolve after the longest-axis collapse. The most idealistic approach for the study of the first filaments would be to use high-resolution N-body simulations for a Λ MDM universe. But, it is still a daunting task to implement the dynamics of the massive neutrinos into the current N-body simulations.

Instead, we choose an analytic approach based on the extended Press-Schechter formalism (Press & Schechter 1974; Lacey & Cole 1993) for this study. Throughout this paper, we assume flat Λ CDM models where the neutrinos have mass and three species $N_\nu = 3$. The key cosmological parameters are set at $\Omega_m = 0.266$, $\Omega_\Lambda = 0.734$, $\Omega_b = 0.0449$, $\sigma_8 = 0.801$ (for the Λ CDM part), $h = 0.710$ and $n_s = 0.963$, to be consistent with WMAP7 results (Komatsu et al. 2011).

The outline of this Paper is as follows. In §2, we derive analytically the rates of merging of the first star forming halos into the first filaments and determine their characteristic mass scales. In §3.1, we evaluate the epochs of the longest-axis collapse of the first filaments and the rates of merging of the first galaxies into the second-generation filaments, and determine their characteristic mass scales. In §4, we explore the possibility of constraining the neutrino mass from the observable mass distribution of the high- z supermassive blackholes. In §5, the results are summarized and a final conclusion is drawn.

2. FORMATION OF THE FIRST FILAMENTS

Recent observations indicate that the first galaxies must have formed in the halos of mass $10^8 - 10^9 M_\odot$ at redshifts $z = 9 - 10$ (e.g., Willott et al. 2009, 2010). What has been inferred from the current high-resolution hydrodynamic simulation is that these first galaxies may have formed through rapid merging of the first-star forming minihalos of mass $10^6 M_\odot$ at $z \geq 20$ (Bromm et al. 2009, and references therein). In this section, we investigate how the presence of massive neutrino would change the evolution channel of the first-star forming halos.

2.1. Variation of the Halo-to-Halo Merging Rates with the Neutrino Mass

In the extended Press-Schechter theory developed by Lacey & Cole (1993, 1994), the key quantity is the conditional probability, $f(M', z'|M, z)$, that a halo of mass M existing at a given redshift z will merge to form a more massive halo of mass $M'(> M)$ at some lower redshift $z'(< z)$. Adopting the spherical collapse condition that a halo of mass M forms at z when its linear density contrast δ on the mass scale M reaches a redshift-dependent threshold $\delta_c/D(z)$ where $\delta_c \approx 1.68$ and $D(z)$ is the linear growth factor, Lacey & Cole (1993) equated this key conditional probability to the differential fraction of the volume in the linear density field occupied by the regions satisfying $\delta' \geq \delta_c/D(z')$ on the mass scale M' at z' provided that it also satisfies the condition of $\delta = \delta_c/D(z)$ on the mass scale M at earlier epoch z .

This key conditional probability $f(M', z'|M, z) dM'$ can now be written as

$$\begin{aligned}
 f(S', \omega'|S, \omega) dS' &\equiv 2 \frac{d}{dS'} p(\delta_{M'} \geq \omega' | \delta_M = \omega) dS' \\
 &= 2 \frac{d}{dS'} \int_{\omega'}^{\infty} p(\delta_{M'} | \delta_M = \omega) d\delta_{M'} dS' \\
 &= \frac{1}{\sqrt{2\pi}} \left[\frac{S}{S'(S - S')} \right]^{3/2} \frac{\omega'(\omega - \omega')}{\omega} \exp \left[-\frac{(\omega'S - \omega S')^2}{2SS'(S - S')} \right] dS', \quad (1)
 \end{aligned}$$

where $f(M', z'|M, z) dM' = f(S', \omega'|S, \omega) dS'$ with $S \equiv \sigma^2(M)$, $\omega \equiv \delta_c(z)$, $S' \equiv \sigma^2(M')$, and $\omega' \equiv \delta_c(z')$. Here $\sigma(M)$ and $\sigma(M')$ are the rms fluctuation of the linear density field smoothed on the mass scale M and M' , respectively. Normalization of σ is done for the Λ MDM linear power spectrum to be identical with the Λ CDM linear power spectrum at large scale. Here, of course, with the normalized Λ CDM linear power spectrum σ at $8h^{-1}\text{Mpc}$ has the value of σ_8 given by WMAP7.

Using Equation (1), Lacey & Cole (1993) calculated the (instantaneous) rate of merging of a dark halo with mass M at a given redshift z into a larger halo with mass M' by taking the derivative of $f(S', \omega'|S, \omega)$ with respect to z' :

$$\frac{d^2 p(M \rightarrow M'|z)}{d \ln \Delta M dz} = - \left| \frac{dS'}{d \ln \Delta M} \right| \left| \frac{d\omega'}{dz'} \frac{d}{d\omega'} f(S', \omega'|S, \omega) \right|_{z'=z} \quad (2)$$

$$= - \frac{\Delta M}{M'^2} \bar{\rho} P_L(k') \frac{d\omega}{dz} \frac{1}{\sqrt{2\pi}} \left[\frac{S}{S'(S - S')} \right]^{3/2} \exp \left[-\frac{\omega^2}{2} \left(\frac{1}{S'} - \frac{1}{S} \right) \right], \quad (3)$$

where $\Delta M \equiv M' - M$ and $P_L(k)$ is the linear density power spectrum for a Λ MDM cosmology. We use the analytic approximation given by Hu & Eisenstein (1998) for the evaluation of $P_L(k)$.

With the help of the above analytic prescriptions, we determine the effect of massive neutrinos on the merging rate of the first star-forming mini-halos of mass $M = 10^6 M_\odot$ at redshift $z = 20$ for the range of the neutrino mass fraction, $0.0 \leq f_\nu \leq 0.13$. We use the analytic formula given by Hu & Eisenstein (1998) for the Λ MDM linear density power spectrum $f_\nu \equiv \Omega_\nu / \Omega_m$ where Ω_ν is the neutrino mass density parameter. The Λ MDM linear growth factor $D(z)$ is approximated as $D_{\Lambda\text{CDM}}^{1-0.6f_\nu}(z)$ where $D_{\Lambda\text{CDM}}(z)$ is the linear growth factor for a Λ CDM universe (Lesgourgues & Pastor 2006). The range of the neutrino mass fraction is chosen to be $0.0 \leq f_\nu \leq 0.13$ where the upper limit of 0.13 comes from the recent WMAP7 constraint (Komatsu et al. 2011). It is also worth mentioning here that for this range of f_ν the mini-halos of mass $10^6 M_\odot$ at $z = 20$ correspond to the $(3 - 4)\sigma$ peaks of the initial density field.

The rates of the merging of the first star-forming mini-halos are plotted as thin lines in Figure 1 for the five different cases of f_ν , which reveals that the halo-to-halo merging rates decrease rapidly as f_ν increases. This result implies that in a Λ MDM universe the free streaming of the massive neutrinos have an effect of deferring the formation of larger halos through the major mergers of the first star-forming mini-halos.

2.2. Variation of the Halo-to-Filament Merging Rate with the Neutrino Mass

The result of §2 indicate that the direct merging of the first mini-halos into larger halos are slowed down by the free streaming of massive neutrinos. But, what about the merging of the first star-forming mini-halos into the first mini-filaments? To derive the rate of merging of the first star-forming mini-halos into the mini-filaments, we adopt the classification scheme proposed by Forero et al. (2009), according to whom a filament of mass M' forms at z' when the two of the three eigenvalues, $\lambda_1, \lambda_2, \lambda_3$, of the linear deformation tensor (defined as the second derivative of the linear peculiar potential) smoothed on the scale of M' exceed the threshold value, $\lambda_c/D(z')$ with $\lambda_c \approx 0.3$. Using the N-body results, they demonstrated that the structures identified by this dynamical classification scheme exhibit indeed filamentary shapes. Their filament-finding scheme is also consistent with the statistical results obtained by Lee & Shandarin (1998).

Adopting this condition for the formation of filaments, we modify the Lacey-Cole formalism to determine the halo-to-filament merging rates. In this modified formalism, the key quantity is the conditional probability, $f(M', z'|M, z)$, that a halo of mass M observed at z will merge into a filament of mass M' formed at z' . We equate this conditional probability to the differential volume fraction occupied by the regions satisfying the filament formation condition, $\lambda_1 \geq \lambda_2 \geq \lambda_c/D(z'), \lambda_3 < \lambda_c/D(z')$ on the mass scale M' at redshift z' provided that the linear density contrast of the same regions, δ , on the smaller mass scale M at earlier epoch z satisfies the spherical collapse condition $\delta = \delta_c/D(z)$. Here δ equals the sum of the three eigenvalues of the deformation tensor smoothed on the mass scale M .

Now, this key conditional probability can be expressed as

$$f(S', \eta'|S, \omega) dS' = 2 \frac{d}{dS'} p(\lambda_1, \lambda_2 \geq \eta', \lambda_3 < \eta' | \delta = \omega) dS', \quad (4)$$

with $\eta' \equiv \lambda_c/D(z')$. To evaluate $f(S', \eta'|S, \omega) dS'$ in Equation (4), it requires us the joint conditional probability distribution of $p(\lambda_1, \lambda_2, \lambda_3 | \delta)$, which has been already derived by Lee (2006) from the original work of Doroshkevich (1970) as

$$p(\lambda_1, \lambda_2, \lambda_3 | \delta) = \frac{p(\lambda_1, \lambda_2, \lambda_3, \delta)}{p(\delta)}$$

$$= \frac{3375}{8\sqrt{5}\pi} \frac{\sigma}{\sigma_{\Delta}\sigma'^6} (\lambda'_{12} - \lambda'_{23})(\lambda'_{23} - \lambda'_{31})(\lambda'_{31} - \lambda'_{12}) \times \exp \left[-\frac{1}{2\sigma_{\Delta}^2} \left(\frac{\sigma'}{\sigma} \delta - \frac{\sigma}{\sigma'} I_1 \right)^2 \right] \exp \left[-\frac{5}{2\sigma'^2} (I_1^2 - 3I_2) \right], \quad (5)$$

where $\sigma \equiv \sigma(M)$, $\sigma' \equiv \sigma(M')$, $\sigma_{\Delta} \equiv \sqrt{\sigma^2 - \sigma'^2}$, $I_1 \equiv \lambda'_{12} + \lambda'_{23} + \lambda'_{31}$ and $I_2 \equiv \lambda'_{12}\lambda'_{23} + \lambda'_{23}\lambda'_{31} + \lambda'_{31}\lambda'_{12}$.

It is now straightforward to calculate the (instantaneous) rate of merging of the first star forming halos of mass $M = 10^6 M_{\odot}$ at $z = 20$ into the early mini-filaments of mass M' as

$$\frac{d^2 p(M \rightarrow M'|z)}{d \ln \Delta M dz} = -\frac{\Delta M}{M'^2} \bar{\rho} P_L(k') \frac{d}{dz'} f(S', \eta'|S, \omega) \Big|_{z'=z}. \quad (6)$$

Figure 1 plots the halo-to-filament merging rates (thick lines). In contrast to the halo-to-halo merging rates, the halo-to-filament merging rates increase with f_{ν} . As f_{ν} changes from 0 to 0.13, the maximum halo-to-filament merging rates increase by a factor of 3. We call the scale on which the halo-to-filament merging rate reaches the maximum value the characteristic filament mass scale and denote it as M_F . For $f_{\nu} \geq 0.07$, the halo-to-filament merging rate begins to exceed 0.1 at the characteristic mass scale around $M_F = 10^9 M_{\odot}$. Whereas for $f_{\nu} \leq 0.04$, the filament-to-halo merging rate is below 0.1 at all filament mass scale. Note that for $f_{\nu} = 0.07$ the mini-halos of mass $10^6 M_{\odot}$ at $z = 20$ tend to merge more rapidly into the mini-filaments of mass $10^9 M_{\odot}$ rather than into the larger halos of mass $10^7 M_{\odot}$. Figure 2 plots the characteristic mass M_F of the first filaments versus the neutrino mass fraction f_{ν} . As one can see, the value of M_F decreases almost linearly with f_{ν} .

3. EVOLUTION OF THE FIRST FILAMENTS

3.1. Longest-Axis Collapse of the First Filaments

In the previous section, it is shown that the first star-forming mini-halos would merger rapidly into the first filament of characteristic mass $\sim 10^9 M_{\odot}$ in the presence of massive neutrinos. As the Universe evolves, these first filaments would ultimately collapse along their longest-axes that are in the direction of the minor principal axes of the local tidal field. To determine the distribution of the redshift z_f when the first filaments collapse along their longest axes, we calculate the conditional probability density that a region satisfying the filament-formation condition ($\lambda_1 \geq \eta, \lambda_2 = \eta, \lambda_3 < \eta$) at $z = 20$ on the mass scale M_F

will meet the halo-formation condition ($\delta = \omega$) at the same mass scale ¹ but at some lower redshift, $z_f < 20$:

$$p(\delta' = \omega' | \lambda_1 \geq \eta, \lambda_2 = \eta, \lambda_3 < \eta) = \frac{\int_{-\infty}^{\eta} d\lambda_3 \int_{\eta}^{\infty} d\lambda_1 p(\delta' = \omega', \lambda_1, \lambda_2 = \eta, \lambda_3)}{\int_{-\infty}^{\eta} d\lambda_3 \int_{\eta}^{\infty} d\lambda_1 p(\lambda_1, \lambda_2 = \eta, \lambda_3)}, \quad (7)$$

where δ' is the linear density contrast on the mass scale M_F at z_f , $\lambda_1, \lambda_2, \lambda_3$ are the three eigenvalues of the deformation tensor smoothed on the mass scale of M_F at $z = 20$, $\omega' \equiv \delta_c/D(z_f)$ and $\eta \equiv \lambda_c/D(z)$. Using the joint probability density distribution of $p(\delta', \lambda_1, \lambda_2, \lambda_3)$ derived by Doroshkevich (1970); Lee (2006), it is also straightforward to evaluate equation (7).

Figure 3 plots this distribution $p(z_f)$ of the epochs of the longest axis collapse of the first filaments for the five different cases of f_ν . As can be seen, $p(z_f)$ has a maximum value at $z_f = 8-9$ for all five cases, which implies that the first filaments retain their structures for a long period from $z = 20$ to $z = 8-9$ without collapsing into zero-dimensional halos. As f_ν increases, however, the distribution $p(z_f)$ becomes narrower and its peak position moves slightly to the lower value of z_f . That is, the massive neutrinos play a role of delaying the longest-axis collapse of the first filaments.

3.2. Formation and Evolution of the Second-Generation Filaments

Now that the halo-to-filament merging rates are found to increase with the neutrino mass fraction, we would like to see how the presence of the massive neutrinos alters the merging rates of the first galaxies. It is naturally expected that some fraction of the first galaxies would also merge first in the filaments (called the second-generation filaments). A question is what the characteristic masses of the second generation filaments are and when they would undergo the longest-axis collapse. To answer this question, we recalculate everything through equations 1-7, but for the first galactic halos of mass $10^9 M_\odot$ at $z = 8$.

Figure 4 plots the halo-to-halo and halo-to-filament merging rates of the first galactic halos of mass $10^9 M_\odot$ at $z = 8$ as thin and thick lines, respectively. A similar trend to that shown in Figure 1 is found for the first galactic halos: As the neutrino mass fraction increases, the halo-to-halo merging rate decreases while the halo-to-filament merging rate increases. The comparison of Figs.1 and 4 also reveals that the halo-to-filament merging rates increases with redshift and with halo mass. For $f_\nu \geq 0.04$, the rate of merging of the first

¹To prevent the mathematical divergence, the mass of a final halo is set at $0.99M_F$.

galaxies into the second generation filaments exceeds 0.1 at all mass scales. The characteristic mass of the second generation filaments is found to lie in range of $10^{11} < M/M_\odot \leq 10^{12}$.

Figure 5 plots the distribution of the redshifts at which the second generation filaments of mass $10^{11}M_\odot$ formed at $z = 8$ experience the longest axis collapse. A similar trend to that shown in Figure 3 is also found: $p(z_f)$ has a maximum value at $z_f = 3-4$ for all five cases, which implies that the second-generation filaments last from $z = 8$ to $z = 3-4$ without collapsing into zero-dimensional halos. The increase of f_ν results in narrowing down the shape of $p(z_f)$ and shifting it slightly to the low- z section. Note that these second generation filaments correspond to filaments hosting galactic halos and are expected to be interconnected to the larger-scale parent filaments of mass $\geq 10^{13} - 10^{14}M_\odot$ (e.g., Springel et al. 2005). The massive galaxies formed through the longest-axis collapse of the second generation filaments would grow through the anisotropic accretion of matter and gas along the larger-scale parent filaments in the cosmic web.

4. CONSTRAINING THE NEUTRINO MASS WITH THE FILAMENT ABUNDANCE

Once the first filaments form through the merging of the first star-forming halos at $z \leq 20$, the first stars comprising the first filaments would grow more rapidly as the accretion of matter and gas occur more efficiently along the bridges of the first filaments (Park & Lee 2009). When the first filaments collapse along their longest axes at $z \sim 8$, the strong collisions between stars and gas particles in the filaments would result in seeding the supermassive blackholes in the massive first galaxies that are believed to power the ultra-luminous high- z quasars (Willott et al. 2010). In this scenario, the high-end slope of the mass distribution of the supermassive blackholes inferred from the observable luminosity function of the ultra-luminous high- z quasars would reflect the mass distribution of the first filaments. Since the mass distribution of the first filaments depend sensitively on the mass of massive neutrinos, it might be possible to constrain the mass of neutrinos by comparing the mass distributions of the first filaments with that of the high- z supermassive blackholes.

The mass distribution function of the first filaments (dN_F/dM) at the epoch of longest-axis collapse (z_f) can be derived by employing the Press-Schechter approach (Press & Schechter 1974):

$$\frac{dN_F(M, z_f)}{dM} = \frac{\bar{\rho}}{M} \left| \frac{d}{dM} F(M, z_f) \right|, \quad (8)$$

where $\bar{\rho}$ is the mean mass density. Here, $F(M, z_f)$ represents the volume fraction occupied by the first filaments of mass larger than M at z_f . Following the Press-Schechter approach,

this volume fraction can be expressed as

$$F(M, z_f) = A p[\lambda_1 \geq \lambda_2 \geq \lambda_{c,z_f}, \lambda_3 \leq \lambda_{c,z_f} | \sigma_M], \quad (9)$$

where A is the normalization factor, λ_s is the value of the λ_2 at the epoch of the longest-axis collapse. Since the first filaments formed at the threshold of $\lambda_c = 0.3$, the value of λ_2 increases gradually till they collapse eventually along their longest axes. It has been found that at the epoch of the longest-axis collapse, λ_2 reaches the critical value of $\lambda_s = 1.0$.

Using the joint distribution, of $p(\lambda_1, \lambda_2, \lambda_3)$, derived by Doroshkevich (1970), it is straightforward to evaluate Equation (8). Figure 6 plots the mass distribution of the first filaments in logarithmic scales at the epoch of the longest-axis collapse for five different cases of the neutrino mass fraction, f_ν . As we have already shown in §2, that the longest-axis collapse of the first filaments occur around $z = 8$, we set z_f at 8 for the evaluation of Equation (8). As it can be seen, in the high-mass section ($M \geq 10^9 h^{-1} M_\odot$), the abundance of the first filaments decreases sharply with M for all cases. The rate of the decrease of the mass function of the first filaments, however, depends sensitively on the value of f_ν . The larger the value of f_ν is, the more rapidly the mass function drops in the high-mass section.

To examine quantitatively how the rate of the decrease of the mass function of the first filaments in the high-mass section changes with f_ν , we approximate it as a power law M^α and determine the value of the high-end slope, α , in the mass range of $10^9 \leq M/(h^{-1} M_\odot) \leq 10^{11}$. Figure 7 plots the high-end slope, α , of the mass distribution of the first filaments versus the neutrino mass fraction, f_ν as solid line. As it can be seen, the absolute value of the high-end slope of the mass function of the first filaments increases sharply as f_ν increases. This result suggests that the value of f_ν could be constrained by using the high-end slope of the mass function of the first filaments. In practice, of course, it is not possible to measure directly the high-end slope of the mass function of the first filaments. As mentioned above, however, we can infer it from the observable high- z blackhole mass function, under the assumption that the longest-axis collapse of the first filaments with mass larger than the characteristic mass ($10^9 h^{-1} M_\odot$) would result in the first galaxies hosting the supermassive blackholes that power the ultra-luminous high- z quasars.

Now, we would like to compare the high-end slope of this theoretically derived mass distribution of the first filaments with that of the observationally obtained mass function of the massive galaxies hosting the high- z supermassive blackholes. Very recently, Willott et al. (2010) have derived the blackhole mass function at $z \sim 6$ from the observed luminosity function of the ultra-luminous high- z quasars (see Figure 8 in Willott et al. 2010). Converting the mass of the high- z supermassive blackholes into the total mass of their host galaxies through the following relation given by Bandara et al. (2009), $\log(M_{\text{bh}}/M_\odot) = (8.18 \pm 0.11) + (1.55 \pm 0.31) \times (\log(M_{\text{tot}}/M_\odot) - 13.0)$, we find the best-fit high-end slope is in the range of

$-6 \leq \alpha \leq -4.3$, which are plotted as two dashed lines in Figure 7. Comparing this range of α against the theoretical curve plotted in Figure 7, it is found that the neutrino mass fraction is constrained as $0.09 \leq f_\nu \leq 0.13$ which corresponds to the neutrino mass range of $0.375 \leq m_\nu/(eV) \leq 0.542$.

5. DISCUSSION AND CONCLUSIONS

Starting with the first star-forming halos of mass $10^6 M_\odot$ at $z = 20$, we have shown analytically that the presence of massive neutrinos opens a new channel for the rapid formation of massive structures by speeding up the halo-to-filament merging process. Once the first filaments of mass $\leq 10^9 M_\odot$ form through the clustering of some of the first star-forming halos at $z \geq 9$, matter and gas would accrete more efficiently along the first filaments, resulting in the fast growth of the constituent halos in the first filaments. As the Universe evolves and the tidal forces increases, the first filaments would undergo the ultimate collapse into the zero-dimensional halos (corresponding to the first massive galaxies) in the directions parallel to the minor principal axes of the local tidal field.

What has been found here is that the longest-axis collapses of the first filaments end up forming the first massive galaxies of mass $\leq 10^9 M_\odot$ at $z \geq 8$. The longest axis collapses of the first filaments would accompany violent mergers among the constituent halos, which in turn would trigger the vigorous star-formation and feed the central blackholes in the resulting first galaxies. Our result suggests that the ultraluminous high- z quasars detected at $z \geq 6$ might correspond to the first massive galaxies formed through the longest-axis collapses of the first filaments.

It has been also found that the second-generation filaments of mass $10^9 M_\odot$ form through the clustering of some of the first galaxies of mass $10^9 M_\odot$ at $z \sim 8$. The first galaxies in the second generation filaments would evolve fast through the filamentary accretion of matter and gas (Park & Lee 2009). When the second generation filaments collapse along their longest axes, they would also induce violent mergers among the constituent galaxies, which would lead to the formation of massive galaxies of mass larger than $10^{11} M_\odot$ with high star-formation rates and large central blackholes at redshifts as high as $z = 3$.

We test the possibility of constraining the neutrino mass, m_ν , from the mass function of the high- z supermassive blackholes that power the ultraluminous high- z quasars, under the assumption that the longest axis collapses of the first filaments would seed the supermassive blackholes. Comparing the high-end slope of the theoretically derived mass function of the first filaments at the epoch of their longest-axis collapse with that of the observed mass func-

tion of the massive first galaxies inferred from the luminosity function of the ultra-luminous high- z quasars, we find that the neutrino mass is constrained to be $0.375 \leq (m_\nu/\text{eV}) \leq 0.542$.

Yet, it is still only a feasibility study. A more comprehensive work should be done to put a robust constraint on m_ν from observational data. First of all, more refined theoretical models for the halo-to-filament merging rates and the abundance of the first filaments should be constructed than the crude approximations based on the extended Press-Schechter formalism, since the formalism has been shown to fail in accurately predicting the merging rates and abundance of bound halos (Fakhouri & Ma 2008). Second, the observational results from the luminosity function of the ultra-luminous high- z quasars still suffer from small-number statistics and thus more quasar data are required. Third, we use the relation given by Bandara et al. (2009) to convert the blackhole mass into the halo mass. However, the relation of Bandara et al. (2009) has been obtained from the blackholes detected at $z \leq 4$, and thus it may not be applicable to the higher- z blackholes. A more accurate relation between the high- z blackhole mass and host halo mass should be found.

Our results also hints that the massive neutrinos may have something to do with the early metal enrichment of the intergalactic medium (IGM). Madau et al. (2001) showed that the early outflows driven by supernovae (SN) ejecta from the galaxies of mass $\geq 10^8 M_\odot$ at $z \sim 9$ would enrich the IGM with the products of stellar nucleosynthesis provided that those galaxies possess relatively high star-formation efficiencies. It is interesting to note that the halo mass and epoch required for the SN-driven outflows are more or less coincident with our estimates for the galactic halos formed through the longest-axis collapse of the first filaments in a Λ MDM model. Assuming that the longest-axis collapse of the first filaments trigger star formation rapidly in the first massive galaxies in a Λ MDM model, the star-formation efficiency of the first mass galaxies may be as high as required for the early metal enrichment by SN-driven outflows. Furthermore, given our speculation that the longest-axis collapse of the first filaments would feed the supermassive blackholes, the anisotropic outflows from the active galactic nuclei (AGN) powered by the supermassive blackholes of the first massive galaxies might also contribute to the early metal enrichment of the IGM (e.g., Germain et al. 2009; Barai et al. 2011). It will be intriguing to explore how the metal enrichment of the IGM depends on the neutrino mass. Our future work is in this direction.

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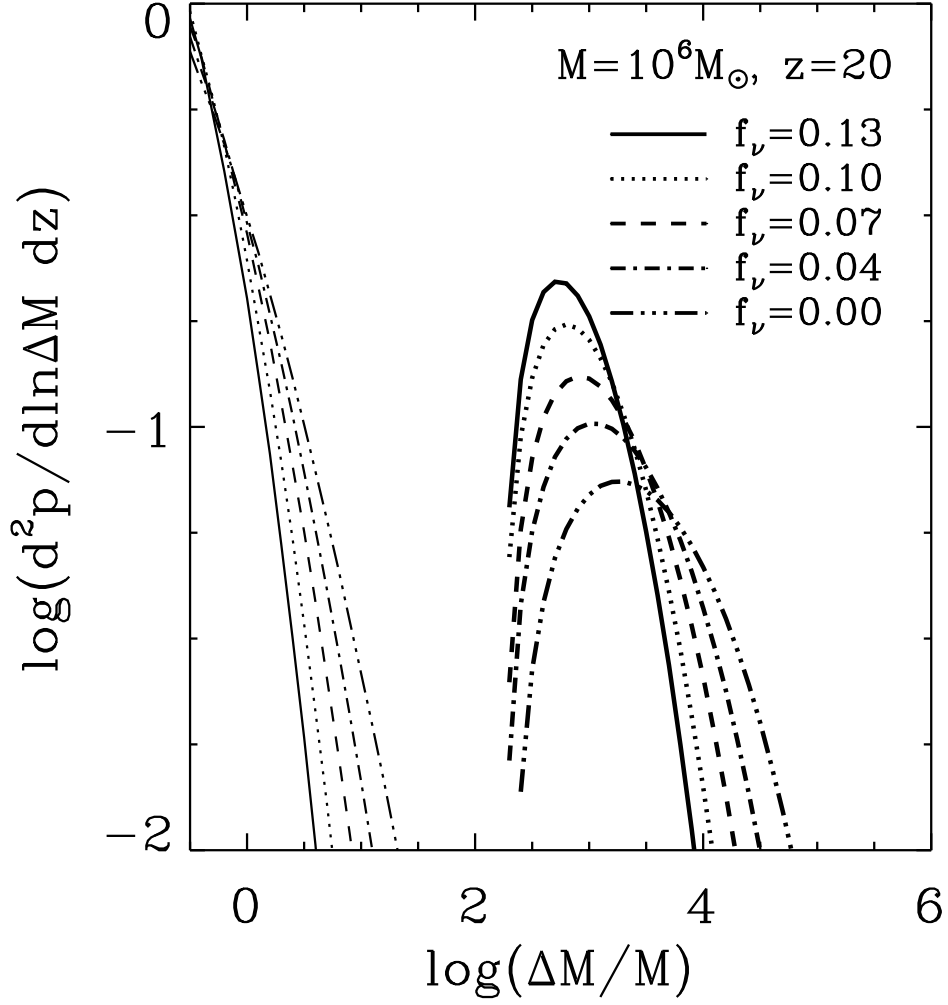


Fig. 1.— Rates of the merging of the first star-forming halos with $M = 10^6 M_\odot$ into the first filaments (thick lines) and larger halos (thin lines) at $z = 20$ for the five different values of the neutrino mass fraction: $f_\nu = 0.13, 0.10, 0.07, 0.04$ and 0.0 (solid, dotted, dashed, dot-dashed, and dot-dot-dashed, respectively).

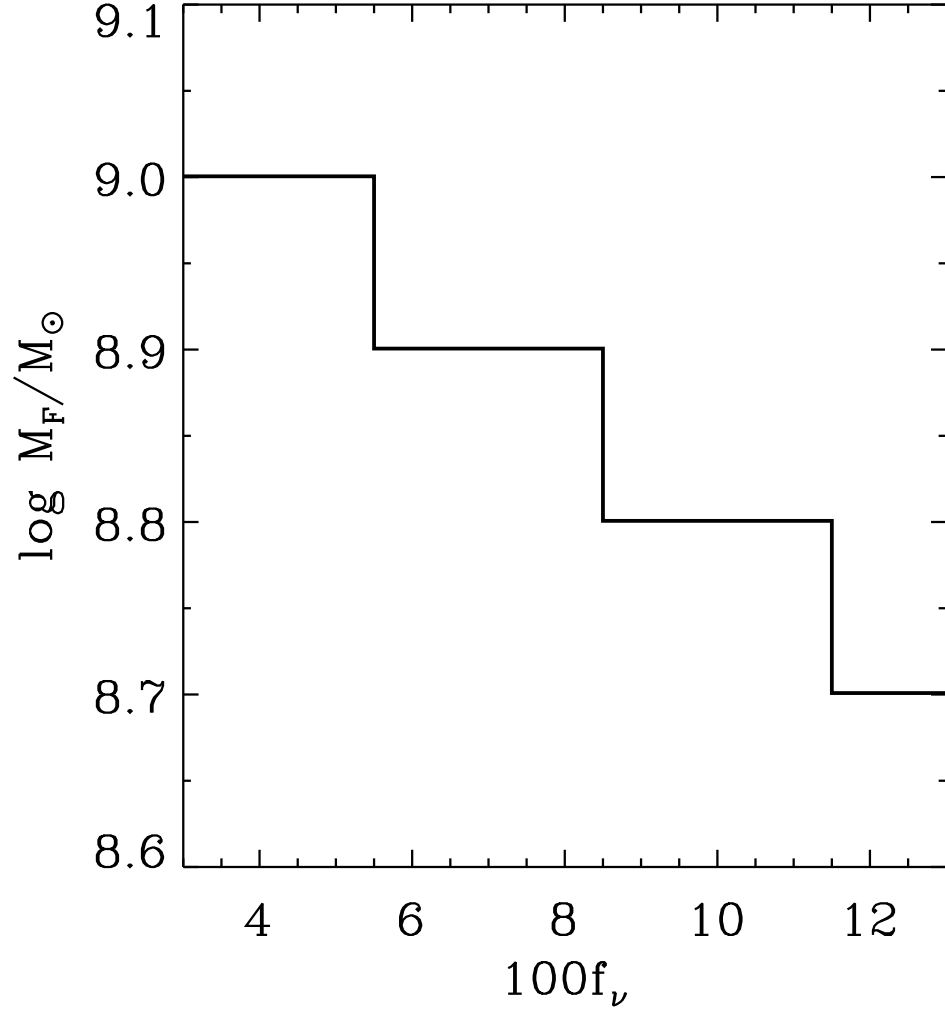


Fig. 2.— Histogram for the characteristic masses of the first filaments versus the neutrino mass fraction f_ν .

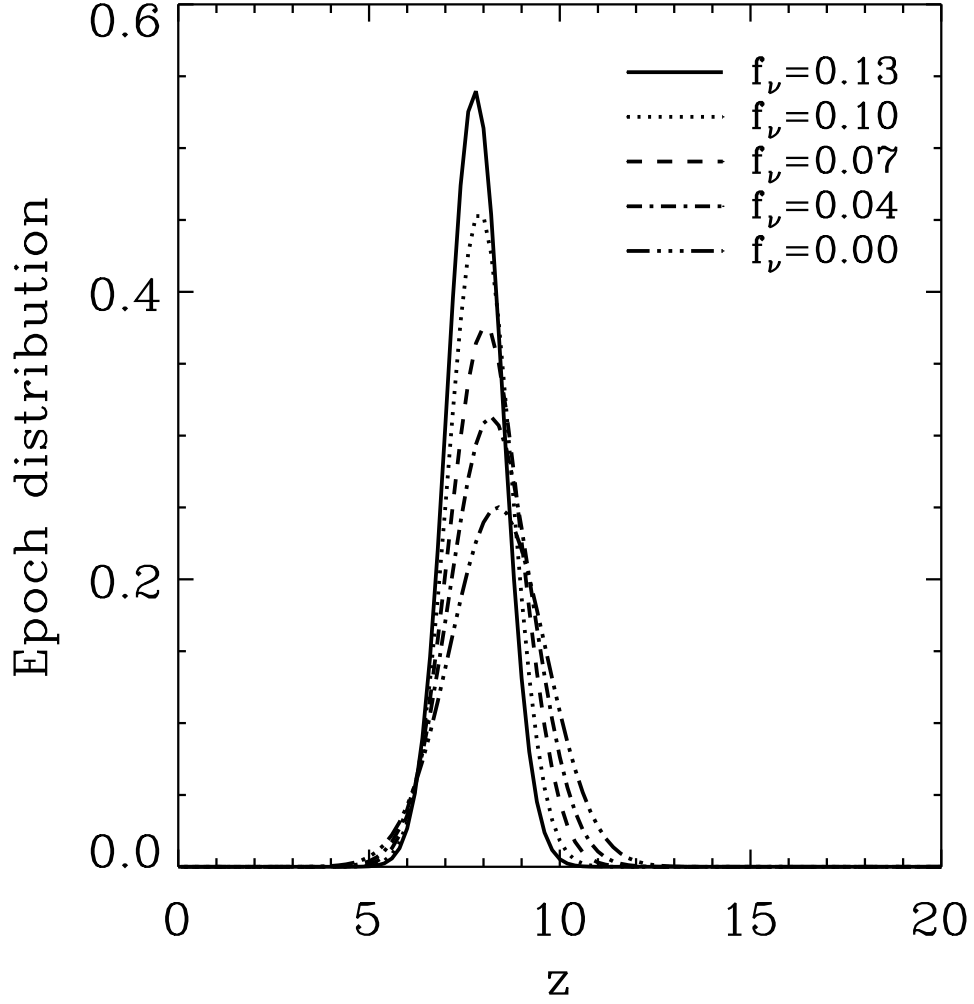


Fig. 3.— Probability density distribution of the redshifts when the longest-axis collapse of the first filaments occur for the first different cases of the neutrino mass fraction: $f_\nu = 0.13, 0.10, 0.07, 0.04$ and 0.0 (solid, dotted, dashed, dot-dashed, and dot-dot-dashed, respectively).

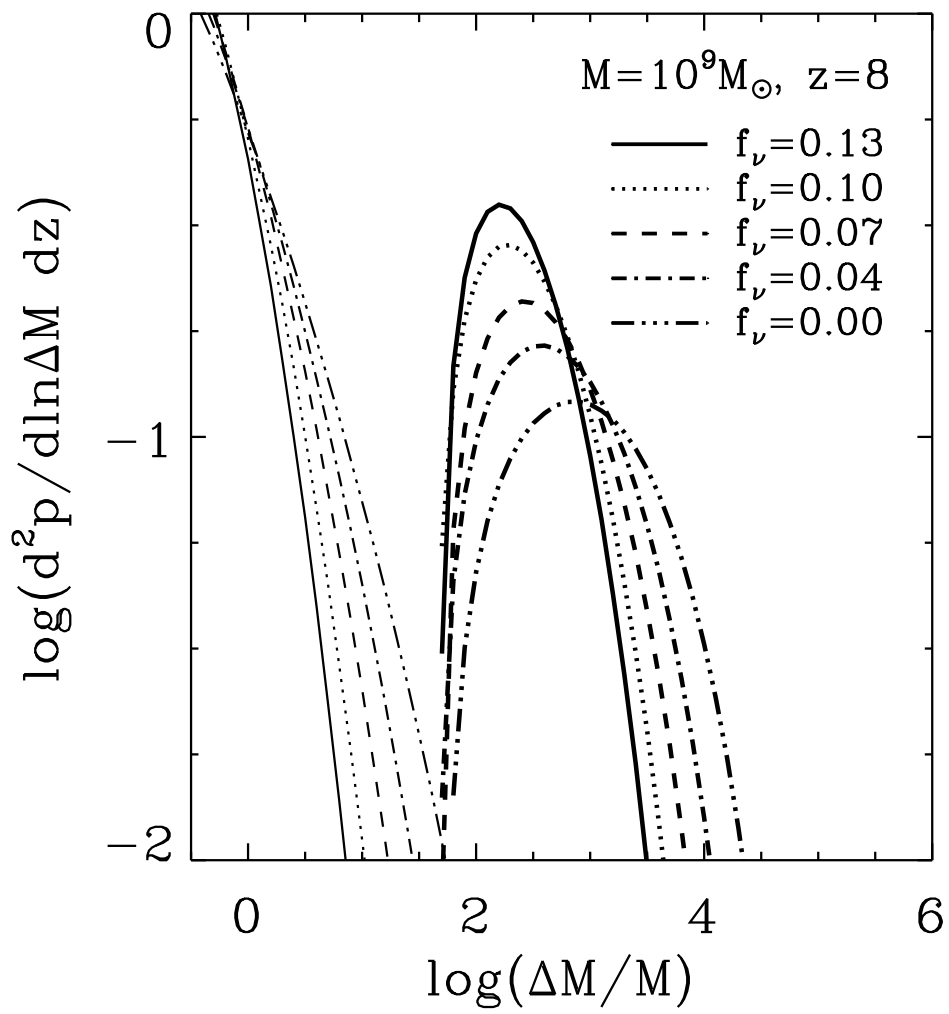


Fig. 4.— Same as Figure 1 but for the first galactic halos of mass $M = 10^9 M_\odot$ at $z = 8$.

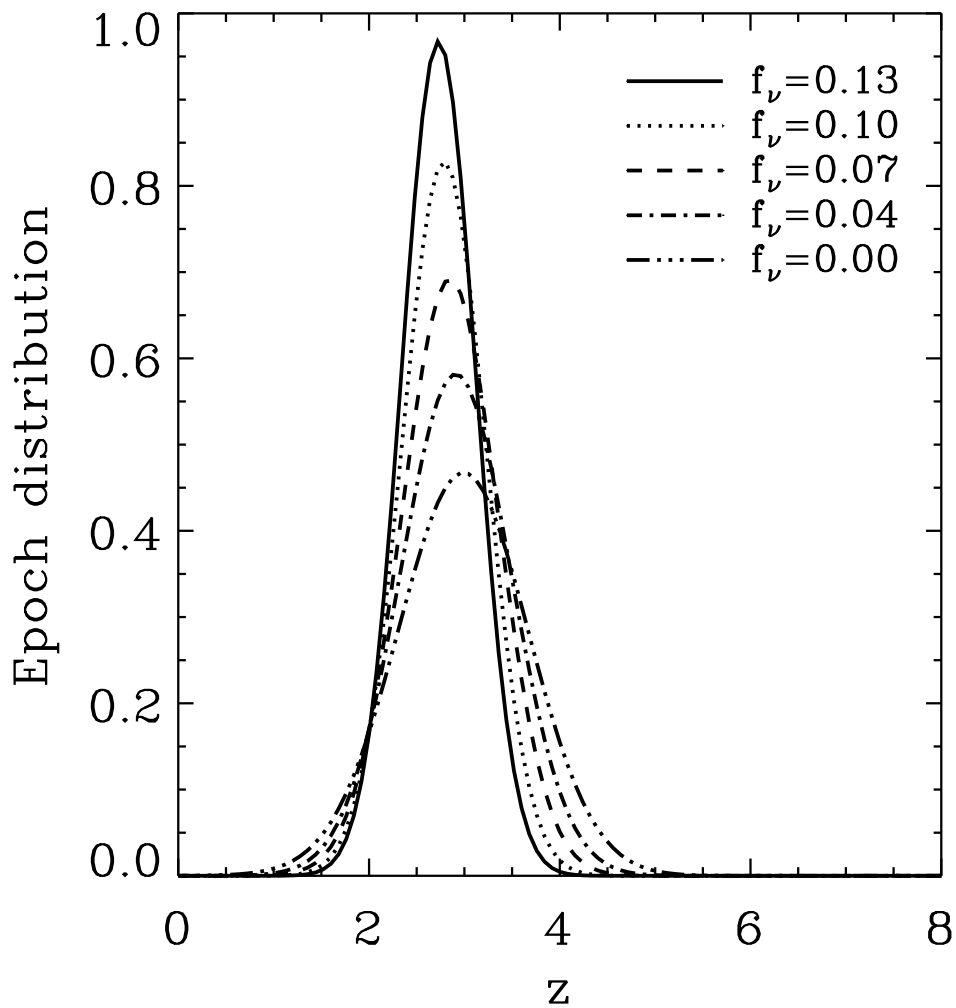


Fig. 5.— Same as Figure 3 but for the second-generation filaments of mass $M = 10^{11} M_{\odot}$.

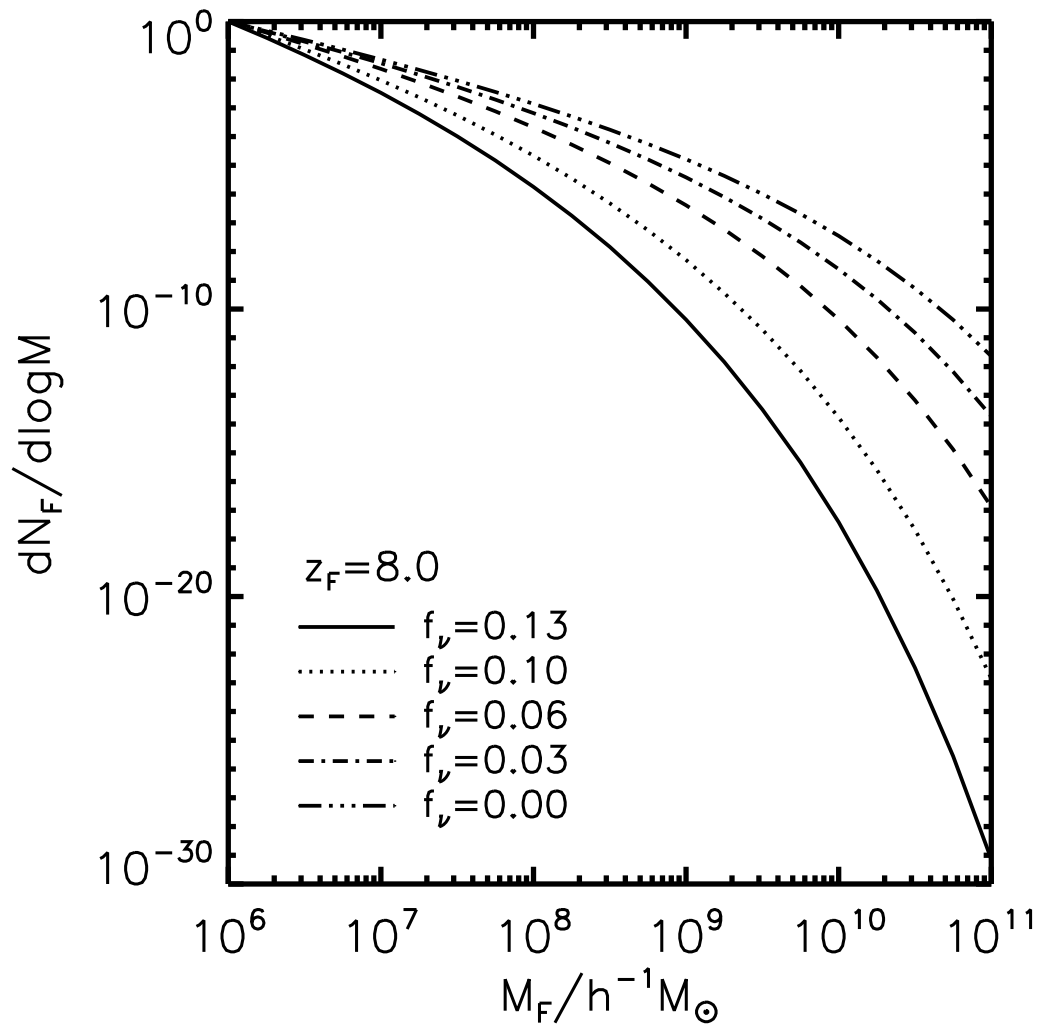


Fig. 6.— Mass distribution of the first filaments for five different cases of the neutrino mass fraction f_ν .

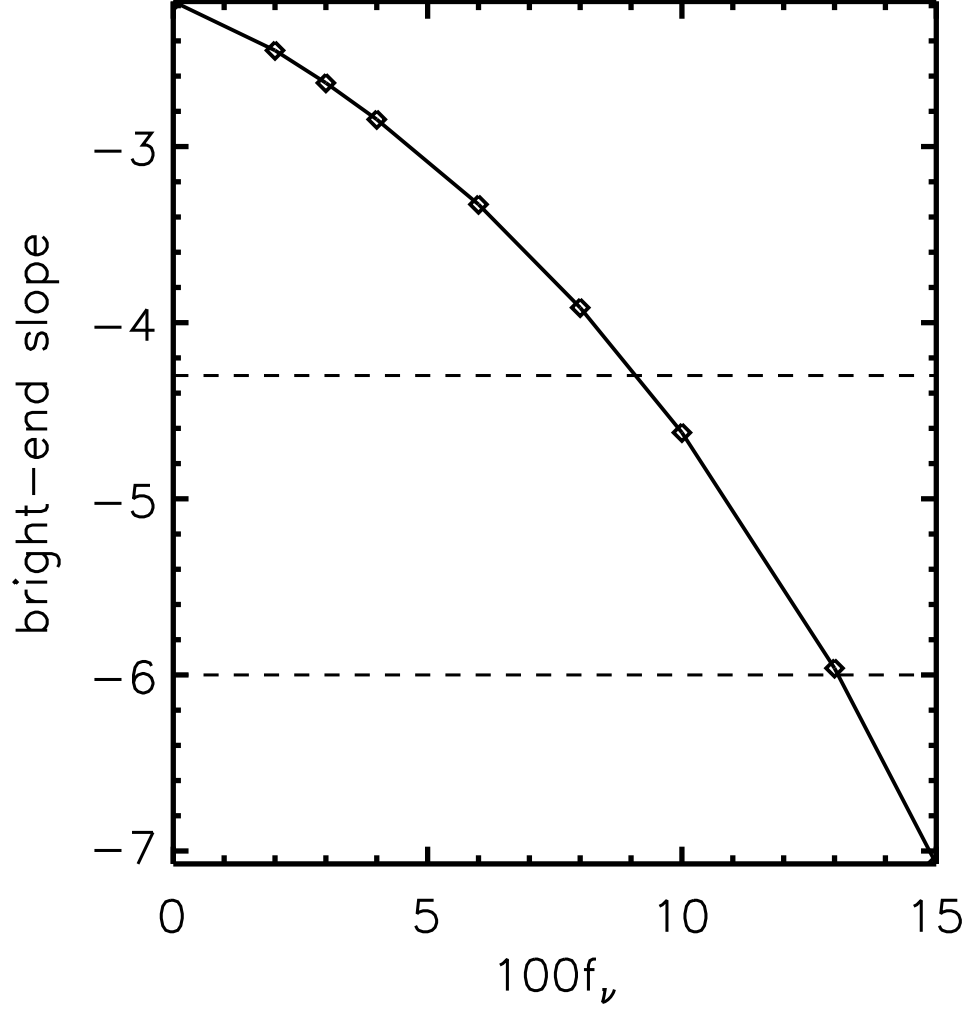


Fig. 7.— High-end slope of the mass function of the first filaments versus f_ν at $z_f = 8$ (solid line). Observational constraints from the mass function of the high- z supermassive blackholes from Willott et al. (2010) are shown as dashed lines.